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ll and Jaime Nickeson, Editors

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Technical Report Series on the Boreal Ecosystem-Atmosphere Study (BOREAS)

Forrest G. Hall and Jaime Nickeson, Editors

Volume 51

BOREAS RSS-7 LAI, Gap Fraction, and FPAR Data

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July 2000

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BOREAS RSS-7 LAI, Gap Fraction, and FPAR Data

Jing M. Chen

Summary

The BOREAS RSS-7 team collected various data sets to develop and validate an algorithm to allow the retrieval of the spatial distribution of LAI from remotely sensed images. Ground measurements of LAI and FPAR absorbed by the plant canopy were made using the LAI-2000 and TRAC optical instruments during focused periods from 09-Aug-1993 to 19-Sep-1994. The measurements were intensive at the NSA and SSA tower sites, but were made just once or twice at auxiliary sites. The final processed LAI and FPAR data set is contained in tabular ASCII files.

Table of Contents

1. Data Set Overview

1.1 Data Set Identification
BOREAS RSS-07 LAI, Gap Fraction, and FPAR Data

1.2 Data Set Introduction
Ground measurements of Leaf Area Index (LAI) and the Fraction of Photosynthetically Active Radiation (FPAR) absorbed by the plant canopy were made in the BOReal Ecosystem-Atmosphere Study (BOREAS) Northern Study Area (NSA) and Southern Study Area (SSA) using optical instruments. The instruments used were the LI-COR LAI-2000 and the Tracing Radiation and Architecture of Canopies (TRAC), which was developed at the Canadian Centre for Remote Sensing (CCRS).

1.3 Objective/Purpose

The objectives of this project were to:

- Obtain LAI and FPAR for the tower sites in both the BOREAS SSA and NSA.
- Describe the spatial variability of LAI and FPAR for the sites.
- Compare methods for indirect measurements of LAI and FPAR. The methods included the LAI-2000 plant canopy analyzer and a sunfleck-LAI instrument, called the TRAC, recently developed at the CCRS.
- Develop algorithms for retrieving LAI and FPAR from Landsat Thematic Mapper (TM) and Advanced Very High Resolution Radiometer (AVHRR) data.
- Investigate the effect of plant canopy architecture on indirect measurements of LAI and FPAR.
- Scale up LAI and FPAR measurements from submeter to km scales National Oceanic and Atmospheric Administration (NOAA) AVHRR pixel scale.

1.4 Summary of Parameters

The following parameters were used:

- LAI-2000: effective LAI
- TRAC: indirect LAI, foliage clumping index, FPAR, PAR albedo of forest floor
- Destructive sampling: ratio of needle area to shoot area

1.5 Discussion

Measurements of LAI were made using two or three units of the LI-COR LAI-2000 plant canopy analyzer. Data were acquired along three 170-m - 300-m parallel transects separated by 10 m at the tower sites and along 50-m transects at the auxiliary sites.

On the same transects, the TRAC was also used to measure LAI, the clumping index, and canopy architectural parameters.

The clumping effect within shoots was determined from laboratory analysis on 27-45 shoot samples for each conifer tower site using a video camera-computer system.

1.6 Related Data Sets

BOREAS RSS-04 1994 Southern Study Area Jack Pine LAI and fPAR Data
BOREAS TE-06 Allometry Data
BOREAS TE-06 NPP for the Tower Flux, Carbon Evaluation, and Auxiliary sites
BOREAS TE-23 Canopy Architecture and Spectral Data from Hemispherical Photos

2. Investigator(s)

2.1 Investigator(s) Name and Title

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Research Scientist

2.2 Title of Investigation

Retrieval of Boreal Forest Leaf Area Index From Multiple Scale Remotely Sensed Vegetation Indices

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3. Theory of Measurements

Parameter definitions for background:

1) LAI

LAI is defined as one half the total green leaf area per unit ground surface area. It has been demonstrated independently by Lang (1991) and Chen and Black (1992a) that this definition is correct for nonflat leaves (including conifer needles) of convex shapes, and it is incorrect to define LAI on the basis of the largest projected area as commonly done before.

It must be pointed out that this definition is given based only on radiation interception by leaves. Plant physiologists concerned with gas exchange and stomatal density and distribution may prefer staying with the total leaf area (in case of concave leaves) or the projected area. It is therefore necessary to know the shape factors that convert between these areas.

2) Plant Area Index (PAI)

PAI is defined as one half the total area of all above-ground plant materials per unit ground surface area. The plant materials include leaves, branches (live or dead), boles, and attachments to plant parts such as lichen and moss. Without the knowledge of the contribution from each of the components, all optical instruments can measure only PAI rather than LAI.

3) Effective LAI (Le)

The term "effective LAI" was used by Chen and Black (1992b) in their earlier papers for the need to provide a measure for the effect of nonrandomness of foliage spatial distribution on indirect measurements of LAI. For conifer forest stands, the effective LAI is considerably smaller than LAI (usually 50%) because leaves are grouped together in tree crowns, branches, shoots, and so on. The grouping or clumping of foliage reduces the light interception and hence effectively reduces LAI derived indirectly from the measurements of canopy gap fraction using equipment such as the LI-COR LAI-2000, hemispherical photography, tram, or moving light sensors. The definition of the effective LAI is:

Effective LAI = Foliage Clumping Index * LAI (1)

The foliage clumping index is smaller than unity for conifer and deciduous stands (usually 0.5).

The LI-COR LAI-2000 measures canopy gap fraction and derives LAI from the gap fraction under the assumption that the foliage elements are randomly distributed in space. Therefore, it measures only the effective PAI (or loosely effective LAI) rather than LAI when the foliage is not random. It is therefore meaningful to report the popular measurements as effective PAI or LI-COR LAI.

Although the effective LAI measured by the LAI-2000 is not LAI, the measurements are still very valuable for estimating the gap fraction and light interception (FPAR and Absorbed Photosynthetically Active Radiation [APAR]) by the canopy, and therefore they should be reported as raw data.

4) Direct LAI and PAI

Direct LAI and PAI are measured directly through destructive sampling. In the measurements, relationships may be used between leaf area and leaf fresh or dry weight, between total leaf area in a branch and the branch diameter or branch weight, and between total leaf area in a tree and the tree diameter at breast height (dbh). In other words, some degree of indirectness may still be involved.

5) Allometric LAI and PAI

These are obtained using pre-established relationships between leaf area and dbh or sapwood area. Sometimes an additional parameter such as crown width, crown length, or an index related to the tree density is used.

6) Indirect LAI and PAI

Indirect LAI and PAI are measured indirectly using optical instruments or by other means. The effective LAI (or more precisely the effective PAI) measured using the LAI-2000 may be corrected to obtain the indirect LAI or PAI. Much research has been done on making such corrections for conifer stands. The corrections include:

i) Needle-to-shoot area ratio (gamma):

Rationale: Conifer needles are tightly grouped together in shoots (an important scale of foliage clumping), and shoots can be treated as the basic foliage units responsible for light interception. This ratio quantifies how much leaf area there is in an average shoot area (if a shoot projection can be approximated by a sphere, it is half the sphere surface area), which is believed to be the quantity measured by the LAI- 2000. Gower and Norman (1991) successfully applied this type of correction to conifer stands of several species. Further investigation has been made by Fassnacht, et al. (1994). The only underlying assumption for making this correction is that shoots are randomly distributed in space.

ii) Shoot clumping index (omega):

Rationale: To consider the effect of clumping at scales larger than shoots. For open conifer stands, shoots are obviously grouped into tree crowns; i.e., the assumption of random spatial distribution of shoots is not met. In this case, an additional parameter concerning foliage clumping at scales larger than the shoot scale becomes very important (Chen and Black 1992a).

Shoot clumping index accounts for the effect of foliage clumping at scales larger than shoots. It can be obtained from analysis of canopy gap size information (Chen and Black, 1992b). The TRAC, developed by RSS-07 at CCRS, is designed to measure sunfleck sizes along straight transects on the forest floor, from which a distribution of canopy gap size is obtained. Measurements using the TRAC show that the shoot clumping index is about 0.70-0.80 for most conifer stands.

iii) Woody-to-total area ratio (alpha):

Rationale: Woody and other nonfoliage materials can have an important contribution to light interception in the canopy, and optical instruments can measure only PAI.

Alpha is the percentage of total green foliage area to the total area of above-ground materials. For closed stands, it is generally larger than 0.9, but for the open boreal stands, the value would be considerably smaller (0.7-0.9).

In conclusion, the following formulae are proposed for calculating the indirect PAI and LAI:

PAI = Effective LAI * gamma/omega (2)

LAI = (1-alpha)* PAI
i.e.
LAI = (1-alpha)*effective LAI*gamma/omega (3)

Gamma is about 1.3 to 1.5 (Gower and Norman, 1991; Chen and Black, 1992b; Fassnacht, et al., 1994; Deblonde, et al., 1994; and Chen 1996a). It is obtained by directly measuring the total leaf area in a detached shoot and the total shoot area (4 times the average projected shoot area) using a computerized video camera system.

From equations 10 and 12, it can be shown that:

Foliage clumping index = Omega/gamma (4)

7) FPAR

Green FPAR is the fraction of incident PAR that is absorbed by the green leaves in the canopy. It excludes the fraction reflected back to the space and the fraction absorbed by the background (moss, soil, and understory in forest), but it includes the small fraction that is reflected by the background and absorbed by the green leaves on the way back to space. The daily green FPAR is the final result reported here after applying a weighting scheme to the instantaneous green FPAR values (Chen, 1996b).

8) PAR Albedo of Forest Floor

This value is calculated as the ratio of the mean values, over a transect, of the transmitted total irradiance and reflected total PAR irradiance from the forest floor using the upward-facing and downward-facing hemispheric PAR sensors of the TRAC.

LI-COR LAI-2000:

There is a certain probability that a beam of radiation passing through some distance of a vegetative canopy will be intercepted by foliage. The probability of interception is proportional to the path length, foliage density, and foliage orientation. Therefore, if the beam transmittance is known, then it is possible to invert foliage information (Welles and Norman, 1991).

Noninterception (i.e., transmittance [T]) is described by Beer's law:

T(zen,azi) = exp (-G(zen,azi) * u * S(zen,azi)) (5)

where G(zen,azi) = fraction of foliage projected toward direction (zen,azi)
u = foliage density (m^2 foliage/ m^3 canopy)
S(zen,azi) = path length through the canopy (m)
zen = zenith angle
azi = azimuth angle

Because the LAI-2000's optical sensor averages over azimuth, the azimuth angle (azi) is omitted from the following equations with the understanding that the various quantities are azimuthal averages. Rewriting equation 5 yields

$$G(zen) * u = - (\ln(T(zen)) / (S(zen)) = K(zen) \qquad (6)$$

K(zen) is the contact frequency, and is equivalent to the average number of contacts per unit length of travel that a beam would make passing through a canopy at zenith angle (zen).

The foliage density u is defined as

$$u = 2 \int_{0}^{\pi/2} K(zen) \sin(zen) \, \partial dzen \qquad (7)$$

Foliage density is related to LAI by canopy height (z):

$$LAI = u * z \qquad (8)$$

Path length S is related to canopy height (z) by zenith angle (zen):

$$S(zen) = z / \cos(zen) \qquad (9)$$

Using equations 6, 7, 8, and 9, LAI can be defined in terms of canopy transmittance:

$$LAI = 2 \int_{0}^{\pi/2} -\ln[T(zen)] \cos(zen) \sin(zen) \, \partial dzen \qquad (10)$$

Because canopy height cancels out of equation 10, it is numerically identical to equation 7 when S(zen)=1/cos(zen). Thus, equation 7 can be used for either LAI or foliage density: if the distances are 1/cos(zen), then the results should be interpreted as LAI; otherwise, foliage density is computed.

Once LAI is estimated from transmittance measurements, five values of G(zen) are determined using equation 6. A straight line is fit to the data, and the slope of that line ($\partial G(zen)/\partial zen$) is used in the following equation to predict mean tilt angle:

$$MTA = 56.82 + 46.85(x) - 64.62(x^2) - 158.69(x^3) + 522.06(x^4) + 1008.15(x^5) \qquad (11)$$

where $x = \partial G(zen)/\partial zen$

However, it must be realized that the above inversion of LAI is based on the assumption that the foliage is randomly distributed in space. This assumption is not met for forest stands, where leaves are grouped into shoots, branches, and tree crowns. Because foliage of forest stands is generally more clumped than random, the LAI-2000 measures the effective LAI (Chen and Black, 1992b) rather than LAI.

TRAC (Tracing Radiation and Architecture of Canopies):

The LAI-2000 measures the canopy gap fraction from which to derive LAI. The canopy gap fraction is the percentage of sky seen from underneath the canopy and carries no information on the actual gap size. The TRAC is designed to obtain the canopy gap size information. The instrument measures the transmitted direct light through the canopy at a high spatial density (1 sample/10 mm) on straight transects near the forest floor. The sunfleck size on the forest floor is thus obtained. From the measured sunfleck size, the corresponding canopy gap size can be calculated after considering the penumbral effect (Chen and Cihlar, 1995a). The distribution of the canopy gap size is a description of the canopy architecture and can be used to quantify the effect of nonrandom foliage spatial distribution on the inversion of LAI from gap fractions. The foliage clumping index is a measure of such an effect and serves as a correction to LAI-2000 measurements. Two methods are useful for deriving the foliage clumping index from a canopy gap size distribution. One is developed by Chen and Black (1992b). They derive the foliage (shoot) clumping index based on the assumptions that foliage elements (shoots) are randomly distributed within foliage clumps (tree crowns), and the foliage clumps are randomly distributed in space. In natural stands, these assumptions are generally acceptable, but the method cannot be applied to plantations, where the assumptions are violated. The second method was recently developed by Chen and Cihlar (1995a). They use a gap removal approach to derive the foliage (shoot) clumping index. In their approach, gaps appearing at probabilities larger than those predicted for the same gap size in a random canopy are truncated or partially removed from the total canopy gap fraction. For this project, Chen and Cihlar's method was used for processing the TRAC data. It is believed to be more accurate than Chen and Black's method because it does not require the assumptions made by Chen and Black.

4. Equipment

4.1 Sensor/Instrument Description

LI-COR LAI-2000:

The LAI-2000 plant canopy analyzer is composed of an LAI-2070 control unit and an LAI-2050 sensor head. The control unit is 21 cm x 11.4 cm x 6.9 cm and has connectors for two sensor heads, two connectors for other LI-COR sensors, and a connector for RS-232 communication. The sensor head projects the image of its nearly hemispheric view onto five detectors arranged in concentric rings (approximately 0-13, 16-28, 32-43, 47-58, 61-74 degrees). Radiation above 490 nm is rejected. Lenses are coated with MgF_2 to improve transmission at high oblique angles. For further information, consult the LAI-2000 plant canopy analyzer instruction manual (LI-COR, 1991).

TRAC:

The TRAC consists of three LI-COR quantum sensors (Model LI-190SB, LI-COR, Lincoln, NE) and a data logger (Campbell Scientific, Logan, UT, Model CR10). Two sensors measure, respectively, the total and diffuse photosynthetic photon flux density (PPFD) transmitted through the forest canopy, and one sensor measures the reflected PPFD from the forest floor.

4.1.1 Collection Environment

Most of the LAI-2000 measurements were made near sunset with the solar elevation angle below 15 degrees to minimize the effect of blue light scattering. The measurements were sometimes also made in overcast conditions. The TRAC was used on clear days only. Sometimes it was operated under sparse cloud conditions, but care was taken to ensure no direct cloud effects on the TRAC measurements.

4.1.2 Source/Platform

- LI-COR LAI-2000: Hand-held in a horizontal position at knee height
- TRAC: Hand-held in a horizontal position at knee height by a person walking on a straight transect on the forest floor.

4.1.3 Source/Platform Mission Objectives

The objectives were to measure and analyze LAI and FPAR taken at various BOREAS sites using the LI-COR LAI-2000 and TRAC instruments.

4.1.4 Key Variables

- From the LI-COR LAI-2000: Effective LAI.
- From the TRAC: Shoot clumping index.
- From shoot sample analysis: needle-to-shoot area ratio.
- From destructive tree sampling: foliage-to-total area ratio

4.1.5 Principles of Operation

LI-COR LAI-2000:

The amount of foliage in a vegetative canopy can be deduced from measurements of radiation attenuation as it passes through the canopy at several angles from the zenith. Foliage orientation information can also be obtained. The LAI-2000 measures the attenuation of diffuse sky radiation at five zenith angles simultaneously. A 90-degree mask was used all the time to prevent interference caused by the operator's presence. The same mask was used for the reference sensor to reduce the influence of the sun. For further information, consult the LAI-2000 plant canopy analyzer instruction manual (LI-COR, 1991).

TRAC:

To obtain the canopy gap size distribution, the direct light transmitted through the canopy is measured at a high spatial density (one sample/10 mm) along straight transects. From the canopy gap size distribution, the shoot clumping index is calculated, which is used as a correction factor for the LAI-2000 measurements, in addition to the correction factor of shoot projection ratio.

4.1.6 Sensor/Instrument Measurement Geometry

LI-COR LAI-2000:

The LAI-2000 was hand-held in a horizontal position at knee height. The LAI-2050 (sensor head) has a near-hemispherical field of view (FOV). The effective view area is:

$$A = pi * H^2 \qquad (12)$$

where A = area
pi = 3.1416
H = canopy height

The potential view area is larger than the effective because the effective range of view is reduced by foliage. The potential area viewed is:

$$A = pi * (3*H)^2 \qquad (13)$$

TRAC:

The TRAC was hand-held in a horizontal position. Two sensors measure, respectively, the total and diffuse PPFD transmitted through the forest canopy, and one sensor measures the reflected PPFD from the forest floor. The view area of the TRAC is hemispherical for diffuse radiation.

4.1.7 Manufacturer of Sensor/Instrument

LI-COR LAI-2000:
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4421 Superior Street
P.O. Box 4425
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(402) 467-3576

TRAC:
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Kanata, Ontario
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Contact: Mr. Mike Kwong
(613) 828-2195
(613) 828-9498 (fax)
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4.2 Calibration

4.2.1 Specifications

LAI-2000:
The front lens of the LAI-2050 sensor head should be kept clean and dry for comparable readings. Recalibration of the sensor head may never be necessary, as long as the optics within the sensor remain in place. The detectors may have long-term electrical drift, but this would not affect LAI determinations.

TRAC:
The LI-COR quantum sensor measures PPFD in the spectral range from 0.4 to 0.7 micrometers. A filter having the transmittance linearly increasing with wavelength is used for this purpose. The filter has sharp cutoffs at both ends of the spectrum. The sensor has a time constant of 10 microseconds.

4.2.1.1 Tolerance

LAI-2000:
It is very difficult (if not impossible) to determine the precision and accuracy of LAI measurements. LAI is estimated by the LAI-2000 from all the light not intercepted by any object in the sensor's FOV (thus, foliage area index would be a more appropriate term).

Some assumptions must be met for accurate estimates of foliage amount and orientation when using the LAI-2000. The degree to which these assumptions are violated will affect the degree to which the calculations can be trusted. The major assumptions are:

- The foliage is black. It is assumed that the below-canopy readings do not include any radiation that has been reflected or transmitted by foliage. There is an optical filter in the LAI-2050 (sensor head) that rejects radiation above 490 nm. In this blue portion of the spectrum, foliage typically reflects and transmits relatively little radiation.
- The foliage is randomly distributed within certain foliage-containing envelopes. These envelopes might be parallel tubes (a row crop), a single ellipsoid (an isolated bush), an infinite box (turf grass), or an infinite box with holes (deciduous forest with gaps).
- The foliage elements are small compared to the view area of each ring. An approximate guideline is this: the distance from the sensor to the nearest leaf over it should be at least four times the leaf width.
- The foliage is azimuthally randomly oriented. That is, it does not matter how the foliage is inclined, as long as all the leaves are not facing the same compass direction.
- The sky brightness is azimuthally uniform.
- Blockage of the sensor's FOV is the same for both incoming and transmitted readings.

No canopy conforms exactly to the first four assumptions. Foliage is never random, but is clumped along stems and branches, and is certainly not black. It was felt that in open boreal forests, the effect of light scattering caused by greyness of leaves is small, and that the LAI-2000 measures the canopy gap fraction or the effective LAI accurately.

TRAC:

The sensor after recalibration is accurate to 98%. The major error arose from the difficulty of maintaining the sensor at a constant horizontal position during measurements. A level is mounted on the holding arm close to the sensor. While walking, the level was watched and the holding arm was adjusted instantly to keep the sensor in a level position. However, because the whole system moves at a walking pace, a slight deviation from the horizontal position is inevitable. The deviation was generally kept within 2 degrees.

The TRAC measures the transmittance of the direct light by subtracting the diffuse fraction from the total irradiance in postmeasurement data processing. The diffuse fraction was identified as a steady baseline appearing in the total irradiance plot for each 10-m section of the transect. The transmittance can be determined with a 97-98% accuracy.

The inversion from the apparent sunfleck size to the corresponding canopy gap size was accurate for large gaps but less accurate for small gaps because of the penumbral effect. A procedure is being developed to minimize this effect (Chen and Cihlar, 1995a).

4.2.2 Frequency of Calibration

LAI-2000:

Two LAI-2000 units were used, one in the forest stand and the other on the ground in an opening to be used as a reference for the above-the-forest-canopy radiation. These two units were calibrated against each other under overcast conditions prior to the field measurements in each Intensive field Campaign (IFC). The calibration procedures are given in the LAI-2000 Plant Canopy Analyzer Instruction Manual, Chapter 4-1 (LI-COR, 1991).

TRAC:

The sensing units, the LI-COR quantum sensors, were calibrated by the manufacturer. Before the 1994 experiment, the sensors were recalibrated against a new LI-COR quantum sensor maintained as a laboratory standard.

4.2.3 Other Calibration Information

Not applicable.

5. Data Acquisition Methods

1993: In August, LAI-2000 measurements were made in the Old Black Spruce (OBS), Old Jack Pine (OJP), and Young Jack Pine (YJP) tower sites in both the SSA and NSA. In each site, measurements were made on three transects parallel to one another and separated by 10 m. The transects are from 170 m to 350 m long, running the flux tower at 135° (SE) and/or 215° (NE). The measurements were made at 10-m intervals along the transects. Two LAI-2000 units were used, one in the forest stands and the other in a nearby opening as the reference. The reference unit was set in a remote logging mode at a sampling frequency of one sample per 15 seconds. The measurements were made in the evening, shortly before and after sunset. The TRAC was also used in the OJP tower site in the NSA and OBS, OJP, and YJP tower sites in the SSA. The measurements were made along the middle transect among the three parallel transects for each site on clear days. The measurements were repeated several times in a day for the same site to obtain the canopy gap size distributions at different solar zenith angles.

1994: Similar LAI-2000 and TRAC measurements were made in IFC-1, -2, and -3 for the tower flux sites. Transect measurements were also made at the SSA-Old Aspen (OA) in a southwest direction from the tower for 300 m. In IFC-2 and -3, both instruments were used at 12 auxiliary sites on two transects oriented S-N and E-W and orthogonal.

The LAI-2000 was used on overcast days or near sunset to minimize the effect of blue light scattering on LAI measurements. The TRAC was used on clear days or on sunny days when the duration of the full sunshine was long enough to permit complete transect measurements.

6. Observations

6.1 Data Notes

None.

6.2 Field Notes

Field notes recorded detailed weather conditions that might affect LAI-2000 and TRAC measurements. These notes are not useful in using the data sets because the results presented here are final, with environmental effects minimized.

7. Data Description

7.1 Spatial Characteristics

7.1.1 Spatial Coverage

Tower and auxiliary sites in the NSA and SSA were visited, although more measurements were concentrated at the forested tower sites.

The maximum length of the transects is about 300 m, which is long enough to obtain the mean value for the stand as long as the stand is homogeneous at large scales. The variation along the transect characterizes the spatial variability.

At the auxiliary sites, two 50-m transects were usually used for the TRAC and LAI-2000 that were perpendicular to each other and crossed in the middle to form a "+" shape.

The locations of the transects at each tower site are reported below relative to the micrometeorological flux tower. All coordinates reported in this section are based on the North American Datum of 1983 (NAD83).

Tower Site Coordinates

Transect	Site	grid ID	Latitude	Longitude	Zone
T-300SE	SSA-OA	C3B7T	53.62937	106.19819	13
150NW-T-150SE	SSA-YJP	F8L6T	53.87581	104.64529	13
T-200SE	SSA-OJP	G2L3T	53.91634	104.69203	13
T-300SE	SSA-OBS	G8I4T	53.98717	105.11779	13
T-300SE	NSA-OBS	T3R8T	55.88007	98.48139	14
170NW-T-260SE	NSA-OJP	T7Q8T	55.92842	98.62396	14
170NW-T-170SE	NSA-YJP	T8S9T	55.89575	98.28706	14
T-300SE	SSA-OA	C3B7T	53.62937	106.19819	13
150NW-T-150SE	SSA-YJP	F8L6T	53.87581	104.64529	13
T-200SE	SSA-OJP	G2L3T	53.91634	104.69203	13
T-300SE	SSA-OBS	G8I4T	53.98717	105.11779	13
T-300SE	NSA-OBS	T3R8T	55.87758	98.47765	14
170NW-T-260SE	NSA-OJP	T7Q8T	55.92842	98.62396	14
170NW-T-170SE	NSA-YJP	T8S9T	55.89575	98.28706	14

Notes: "150NW-T-150SE" means that the measurements were made on transects from 150 m northwest of the flux tower to 150 m southeast of the tower. T-300SE means that the measurements were made on transects from the tower to 300 m southeast of the tower. There were always three transects parallel to one another and separated by 10 m. LAI-2000 measurements were made at 10-m intervals, while TRAC measurements were made continuously (1-cm interval for the transmitted PAR) along the transects.

The auxiliary sites listed below were visited:

SSA:

BORIS Grid	notes	West Longitude	North Latitude	UTM Easting	UTM Northing	UTM Zone
F7J0P	JMH-5	105.05115	53.88336	496667	5970323.3	13
F7J1P	JMH-A2	105.03226	53.88211	497879.4	5970405.6	13
G2I4S	BMH	105.13964	53.93021	490831.4	5975766.3	13
G9I4S	BDL-20	105.11805	53.99877	492291.2	5983169.1	13
BMM-1	BMM-1aa	105.28275	53.65383	481312.5	5945044.9	13
BMM-2	BMM-1ab	105.28705	53.65411	481028.4	5945077.2	13
BMM-3	BMM-1ac	105.28807	53.65393	480960.9	5945057.4	13
G1K9P	JMM-6	104.74812	53.9088	516546.7	5973404.5	13

Note: BMM-1, BMM-2, and BMM-3 are Remote Sensing Science (RSS-07) sites (the RSS-07 team did not find the BOREAS auxiliary site BMM-1 (D0H6S), and therefore set up its own sites. Darcy Snell later surveyed them with the Global Positioning System (GPS) and reported them as BMM-1aa, BMM-1ab, and BMM-1ac.

NSA:

BORIS Grid	notes	West Longitude	North Latitude	UTM Easting	UTM Northing	UTM Zone
T2Q6A	TE Carbon	98.67479	55.88691	520342	6193540.7	14
T6R5S	BIH-9	98.51865	55.90802	530092	6195947	14
T7R9S	BDH-3	98.44877	55.91506	534454.5	6196763.6	14
T8Q9P	JIH-2	98.6105	55.93219	524334.5	6198601.4	14
T6T6S	BIL-2	98.18658	55.87968	550887.9	6192987.9	14
T8S4S		98.37111	55.91689	539306.4	6197008.6	14
T8T1P	JDM-1	98.26269	55.90539	546096.3	6195795.3	14
T9Q8P	JIL-1	98.59568	55.93737	525257.1	6199183.2	14
T7T3S	BML-21	98.22621	55.89358	548391.8	6194505.6	14

7.1.2 Spatial Coverage Map
Not available.

7.1.3 Spatial Resolution
Not applicable for LAI-2000. The spatial resolution of LAI measured by the TRAC is 100 mm, which is 10 times the measurement interval of 10 mm. The height of TRAC measurements was lowered to 10-20 cm from the ground in SSA-YJP and NSA-YJP, where trees are short (1-5 m), to include all foliage above ground. The sensor height is less critical in mature stands, where trees are about 10 m and higher.

7.1.4 Projection
Not applicable.

7.1.5 Grid Description
Not applicable.

7.2 Temporal Characteristics

7.2.1 Temporal Coverage
Measurements with the LAI-2000 began at about 20 minutes before sunset or under overcast sky

conditions. Measurements at a location typically took half a minute and about 30-45 minutes for a whole stand with about 90 measurement locations. Measurements with the TRAC were made under clear sky conditions. In 1994, the LAI measurements were made for the same sites in IFC-1, -2, and -3 to show the seasonal variation.

7.2.2 Temporal Coverage Map

Dates and Instruments Used at the Various Sites

Date	Site	LAI-2000	TRAC
15-Aug-93	NOJP	x	x
16-Aug-93	NYJP	x	
17-Aug-93	NOBS	x	
19-Aug-93	SOJP	x	x
20-Aug-93	SYJP		x
21-Aug-93	SYJP		x
22-Aug-93	SYJP	x	
23-Aug-93	SOBS	x	
24-Aug-93	SOBS	x	
25-Aug-93	SOBS	x	
25-Aug-93	SOJP	x	
27-Aug-93	SOA	x	x
26-May-94	SOJP		x
27-May-94	SOJP		x
30-May-94	SOJP	x	
31-May-94	SOBS		x
01-Jun-94	SOA		x
02-Jun-94	SOBS		x
02-Jun-94	SOA	x	
03-Jun-94	SYJP	x	
04-Jun-94	SOBS	x	
06-Jun-94	SYJP		x
07-Jun-94	NOJP		x
08-Jun-94	NOA (aux)		x
09-Jun-94	NYJP		x
10-Jun-94	NOBS	x	x
11-Jun-94	NOA	x	
11-Jun-94	NOJP	x	
13-Jun-94	NYJP	x	x
28-Jun-94	W0Y5A	x	
29-Jun-94	T4U9S	x	
01-Jul-94	T8T1P	x	
01-Jul-94	T8S4S	x	
01-Jul-94	T6T6S	x	

Date	Site	LAI-2000	TRAC
23-Jul-94	SOBS		x
24-Jul-94	SOJP		x
26-Jul-94	SYJP		x
27-Jul-94	SYJP	x	
27-Jul-94	Sfen	x	x
28-Jul-94	SOA	x	
29-Jul-94	SOBS	x	
29-Jul-94	SOJP	x	
31-Jul-94	Nfen		x
02-Aug-94	NYJP	x	x
03-Aug-94	NOA	x	
03-Aug-94	NOJP	x	
04-Aug-94	NOBS	x	x
30-Aug-94	NOJP	x	
31-Aug-94	NOJP		x
31-Aug-94	NYJP		x
01-Sep-94	t7t3s,t7r9s		x
02-Sep-94	NOBS	x	x
03-Sep-94	Nfen,t6r5s		x
05-Sep-94	NYJP	x	
06-Sep-94	Nfen	x	
06-Sep-94	NOJP,t8q8p		x
07-Sep-94	NOJP	x	x
08-Sep-94	NOA	x	
08-Sep-94	Aux Sites (t3u9s,t6r8s, t7r9s,t7t3s, t8q9p)	x	
10-Sep-94	SOJP	x	
10-Sep-94	SYJP	x	
10-Sep-94	Sfen	x	
11-Sep-94	SOBS	x	
12-Sep-94	Sfen		x
12-Sep-94	SYJP		x
12-Sep-94	SOJP		x
13-Sep-94	SOBS		x
16-Sep-94	Aux Sites (g1k9p,g2l7s)		x
17-Sep-94	SOA		x
18-Sep-94	Aux Sites (g2i4s,g3i4m, g9i4s,f7j0p, f7j1p)	x	x

In addition to these optical measurements, 27-45 conifer shoot samples were taken from each stand in each IFC 1994 for laboratory analysis of the needle-to-shoot area ratio and other shoot properties. In IFC-3 1994, destructive sampling of LAI was made in NSA-OJP, SSA-OJP, and SSA-OBS. All the above measurements were reported in Chen (1996a). Shoot angle measurements were made in IFC-3 1994 in SSA-YJP, SSA-OBS, and NSA-YJP. These measurements are reported in Chen (1996b).

7.2.3 Temporal Resolution

Measurements of the LAI-2000 began at about 20 minutes before sunset or under overcast sky conditions. Measurements at a location typically took half a minute and about 30-45 minutes for a whole stand with about 90 measurement locations.

7.3 Data Characteristics

7.3.1 Parameter/Variable

The parameters contained in the data files on the CD-ROM are:

LAI, Gap Fraction, and FPAR Data:

```
         Column Name
------------------------------
SITE_NAME
SUB_SITE
START_DATE
END_DATE
OP_GRID_INFO
SOLAR_ZEN_ANG
DAILY_GREEN_FPAR
LAI_STD_METHOD
EFFECTIVE_LAI
ELEMENT_CLUMPING_INDEX
FOLIAGE_TO_TOTAL_AREA_RATIO
NEEDLE_TO_SHOOT_AREA_RATIO
PLANT_AREA_INDEX
FOREST_FLOOR_ALBEDO
CRTFCN_CODE
REVISION_DATE
```

Effective LAI

```
         Column Name
------------------------------
SITE_NAME
SUB_SITE
DATE_OBS
TIME
TRANSECT
DISTANCE
EFFECTIVE_LAI
CRTFCN_CODE
REVISION_DATE
```

7.3.2 Variable Description/Definition

The descriptions of the parameters contained in the data files on the CD-ROM are:

LAI, Gap Fraction, and FPAR Data

Column Name	Description
SITE_NAME	The identifier assigned to the site by BOREAS, in the format SSS-TTT-CCCCC, where SSS identifies the portion of the study area: NSA, SSA, REG, TRN, and TTT identifies the cover type for the site, 999 if unknown, and CCCCC is the identifier for site, exactly what it means will vary with site type.
SUB_SITE	The identifier assigned to the sub-site by BOREAS, in the format GGGGG-IIIII, where GGGGG is the group associated with the sub-site instrument, e.g. HYD06 or STAFF, and IIIII is the identifier for sub-site, often this will refer to an instrument.
START_DATE	The date on which the collection of data commenced.
END_DATE	The date on which the collection of the data was terminated.
OP_GRID_INFO	The site identifier used by this RSS team during the execution of field operations. This is used to further link data to site information contained elsewhere.
SOLAR_ZEN_ANG	The angle from the surface normal (straight up) to the sun during the data collection.
DAILY_GREEN_FPAR	Fraction of photosynthetically active radiation absorbed by green plant material over the course of a day.
LAI_STD_METHOD	Leaf angle index calculated by the standard method with the LICOR LAI-2000.
EFFECTIVE_LAI	A measure for the effect of non-randomness of foliage spatial distribution on indirect measurements of LAI
ELEMENT_CLUMPING_INDEX	An index of the amount of grouping or clumping in tree crowns, branches, and shoots
FOLIAGE_TO_TOTAL_AREA_RATIO	The ratio of total green foliage area to the total area of above-ground materials.
NEEDLE_TO_SHOOT_AREA_RATIO	The rates of needle to shoot area which quantifies how much leaf area there is in an average shoot area
PLANT_AREA_INDEX	The plant area index is defined as half the total area of all above-ground plant materials per unit ground surface area
FOREST_FLOOR_ALBEDO	The albedo measurement of the forest floor.
CRTFCN_CODE	The BOREAS certification level of the data. Examples are CPI (Checked by PI), CGR (Certified by Group), PRE (Preliminary), and CPI-??? (CPI but questionable).
REVISION_DATE	The most recent date when the information in the referenced data base table record was revised.

Effective LAI

Column Name	Description
SITE_NAME	The identifier assigned to the site by BOREAS, in the format SSS-TTT-CCCCC, where SSS identifies the portion of the study area: NSA, SSA, REG, TRN, and TTT identifies the cover type for the site, 999 if unknown, and CCCCC is the identifier for site, exactly what it means will vary with site type.
SUB_SITE	The identifier assigned to the sub-site by BOREAS, in the format GGGGG-IIIII, where GGGGG is the group associated with the sub-site instrument, e.g. HYD06 or STAFF, and IIIII is the identifier for sub-site, often this will refer to an instrument.
DATE_OBS	The date on which the data were collected.
TIME	The Greenwich Mean Time (GMT) when the data were collected.
TRANSECT	Designation for transect identifier within site.
DISTANCE	Distance from the tower along the transect.
EFFECTIVE_LAI	A measure for the effect of non-randomness of foliage spatial distribution on indirect measurements of LAI
CRTFCN_CODE	The BOREAS certification level of the data. Examples are CPI (Checked by PI), CGR (Certified by Group), PRE (Preliminary), and CPI-??? (CPI but questionable).
REVISION_DATE	The most recent date when the information in the referenced data base table record was revised.

7.3.3 Unit of Measurement

The measurement units for the parameters contained in the data files on the CD-ROM are:

LAI, Gap Fraction, and FPAR Data

Column Name	Units
SITE_NAME	[none]
SUB_SITE	[none]
START_DATE	[DD-MON-YY]
END_DATE	[DD-MON-YY]
OP_GRID_INFO	[none]
SOLAR_ZEN_ANG	[degrees]
DAILY_GREEN_FPAR	[unitless]
LAI_STD_METHOD	[unitless]
EFFECTIVE_LAI	[unitless]
ELEMENT_CLUMPING_INDEX	[unitless]
FOLIAGE_TO_TOTAL_AREA_RATIO	[unitless]
NEEDLE_TO_SHOOT_AREA_RATIO	[unitless]
PLANT_AREA_INDEX	[unitless]
FOREST_FLOOR_ALBEDO	[percent]
CRTFCN_CODE	[none]
REVISION_DATE	[DD-MON-YY]

Effective LAI

Column Name	Units
SITE_NAME	[none]
SUB_SITE	[none]
DATE_OBS	[DD-MON-YY]
TIME	[HHMMSS GMT]
TRANSECT	[none]
DISTANCE	[meters]
EFFECTIVE_LAI	[unitless]
CRTFCN_CODE	[none]
REVISION_DATE	[DD-MON-YY]

7.3.4 Data Source

The sources of the parameter values contained in the data files on the CD-ROM are:

LAI, Gap Fraction, and FPAR Data

Column Name	Data Source
SITE_NAME	[Assigned by BORIS]
SUB_SITE	[Assigned by BORIS]
START_DATE	[Controller]
END_DATE	[Controller]
OP_GRID_INFO	[Designation given by BORIS or PI]
SOLAR_ZEN_ANG	[Calculated]
DAILY_GREEN_FPAR	[TRAC]
LAI_STD_METHOD	[LAI-2000 and TRAC]
EFFECTIVE_LAI	[LAI-2000]
ELEMENT_CLUMPING_INDEX	[TRAC]
FOLIAGE_TO_TOTAL_AREA_RATIO	[Destructive tree sampling]
NEEDLE_TO_SHOOT_AREA_RATIO	[AgVision camera-light table system]
PLANT_AREA_INDEX	[LAI-2000 and TRAC]
FOREST_FLOOR_ALBEDO	[TRAC]
CRTFCN_CODE	[Assigned by BORIS]
REVISION_DATE	[Assigned by BORIS]

Effective LAI

Column Name	Data Source
SITE_NAME	[Assigned by BORIS]
SUB_SITE	[Assigned by BORIS]
DATE_OBS	[Controller]
TIME	[Controller]
TRANSECT	[PI designation]
DISTANCE	[Measured by PI]
EFFECTIVE_LAI	[LAI-2000]
CRTFCN_CODE	[Assigned by BORIS]
REVISION_DATE	[Assigned by BORIS]

7.3.5 Data Range

The following table gives information about the parameter values found in the data files on the CD-ROM.

LAI, Gap Fraction, and FPAR Data

Column Name	Minimum Data Value	Maximum Data Value	Missng Data Value	Unrel Data Value	Below Detect Limit	Data Not Cllctd
SITE_NAME	NSA-9BS-9TETR	SSA-YJP-FLXTR	None	None	None	None
SUB_SITE	RSS07-LAI01	RSS07-LAI01	None	None	None	None
START_DATE	09-AUG-93	17-SEP-94	None	None	None	None
END_DATE	29-AUG-93	19-SEP-94	None	None	None	None
OP_GRID_INFO	N/A	N/A	None	None	None	None
SOLAR_ZEN_ANG	32.4	50.9	None	None	None	Blank
DAILY_GREEN_FPAR	.38	.93	None	None	None	Blank
LAI_STD_METHOD	1.06	5.37	None	None	None	Blank
EFFECTIVE_LAI	0	2.75	None	None	None	Blank
ELEMENT_CLUMPING_ INDEX	1	1.52	None	None	None	Blank
FOLIAGE_TO_TOTAL_ AREA_RATIO	.7	.95	None	None	None	Blank
NEEDLE_TO_SHOOT_ AREA_RATIO	.68	.97	None	None	None	Blank
PLANT_AREA_INDEX	1.61	5.74	None	None	None	Blank
FOREST_FLOOR_ALBEDO	5.2	11	None	None	None	Blank
CRTFCN_CODE	CPI	CPI	None	None	None	None
REVISION_DATE	31-OCT-96	26-JUN-98	None	None	None	None

Effective LAI

Column Name	Minimum Data Value	Maximum Data Value	Missng Data Value	Unrel Data Value	Below Detect Limit	Data Not Cllctd
SITE_NAME	NSA-OBS-FLXTR	SSA-YJP-FLXTR	None	None	None	None
SUB_SITE	RSS07-EFL01	RSS07-EFL01	None	None	None	None
DATE_OBS	30-MAY-93	13-JUN-94	None	None	None	None
TIME	134330	221611	None	None	None	None
TRANSECT	A	TRAM	None	None	None	None
DISTANCE	0	300	None	None	None	None
EFFECTIVE_LAI	.51	3.79	None	None	None	None
CRTFCN_CODE	CPI	CPI	None	None	None	None
REVISION_DATE	06-NOV-96	06-NOV-96	None	None	None	None

Minimum Data Value -- The minimum value found in the column.
Maximum Data Value -- The maximum value found in the column.
Missng Data Value -- The value that indicates missing data. This is used to indicate that an attempt was made to determine the parameter value, but the attempt was unsuccessful.
Unrel Data Value -- The value that indicates unreliable data. This is used to indicate an attempt was made to determine the parameter value, but the value was deemed to be unreliable by the analysis personnel.
Below Detect Limit -- The value that indicates parameter values below the

```
                      instruments detection limits.  This is used to
                      indicate that an attempt was made to determine the
                      parameter value, but the analysis personnel determined
                      that the parameter value was below the detection
                      limit of the instrumentation.
Data Not Cllctd    -- This value indicates that no attempt was made to
                      determine the parameter value.  This usually
                      indicates that BORIS combined several similar but
                      not identical data sets into the same data base table
                      but this particular science team did not
                      measure that parameter.

Blank -- Indicates that blank spaces are used to denote that type of value.
N/A   -- Indicates that the value is not applicable to the respective column.
None  -- Indicates that no values of that sort were found in the column.
--------------------------------------------------------------------------------
```

7.4 Sample Data Format

The following are sample records from the data file on the CD-ROM:

Effective LAI

```
SITE_NAME,SUB_SITE,DATE_OBS,TIME,TRANSECT,DISTANCE,EFFECTIVE_LAI,CRTFCN_CODE,
REVISION_DATE
'NSA-OBS-FLXTR','RSS07-EFL01',10-JUN-94,200227,'C',10,2.34,'CPI',06-NOV-96
'NSA-OBS-FLXTR','RSS07-EFL01',10-JUN-94,200349,'C',20,2.49,'CPI',06-NOV-96
'NSA-OBS-FLXTR','RSS07-EFL01',10-JUN-94,200949,'C',30,2.46,'CPI',06-NOV-96
'NSA-OBS-FLXTR','RSS07-EFL01',10-JUN-94,201029,'C',40,2.23,'CPI',06-NOV-96
'NSA-OBS-FLXTR','RSS07-EFL01',10-JUN-94,201050,'A',10,3.04,'CPI',06-NOV-96
'NSA-OBS-FLXTR','RSS07-EFL01',10-JUN-94,201106,'C',50,2.45,'CPI',06-NOV-96
```

LAI, Gap Fraction, and FPAR Data

```
SITE_NAME,SUB_SITE,START_DATE,END_DATE,OP_GRID_INFO,SOLAR_ZEN_ANG,
DAILY_GREEN_FPAR,LAI_STD_METHOD,EFFECTIVE_LAI,ELEMENT_CLUMPING_INDEX,
FOLIAGE_TO_TOTAL_AREA_RATIO,NEEDLE_TO_SHOOT_AREA_RATIO,PLANT_AREA_INDEX,
FOREST_FLOOR_ALBEDO,CRTFCN_CODE,REVISION_DATE
'SSA-YJP-FLXTR','RSS07-LAI01',24-MAY-94,05-JUN-94,'F8L6T',32.4,.68,2.86,1.51,
1.43,.72,.95,2.98,,'CPI',31-OCT-96
'SSA-YJP-FLXTR','RSS07-LAI01',24-MAY-94,19-SEP-94,'F8L6T',,,,,,,,6.2,'CPI',
26-JUN-98
'SSA-9OA-FLXTR','RSS07-LAI01',02-JUN-94,02-JUN-94,'C3B7T',32.4,.74,2.26,2.02,1.0,
.77,.92,2.63,,'CPI',31-OCT-96
'NSA-9BS-9TETR','RSS07-LAI01',06-JUN-94,16-JUN-94,'T6R5S',33.0,.86,4.29,,,,,,
'CPI',11-NOV-96
```

8. Data Organization

8.1 Data Granularity

The unit of data tracked by the BOREAS Information System (BORIS) is all the data collected at a site on a given day or for a given time period.

8.2 Data Format(s)

The Compact Disk-Read-Only Memory (CD-ROM) files contain American Standard Code for Information Interchange (ASCII) numerical and character fields of varying length separated by commas. The character fields are enclosed with single apostrophe marks. There are no spaces between the fields.

Each data file on the CD-ROM has four header lines of Hyper-Text Markup Language (HTML) code at the top. When viewed with a Web browser, this code displays header information (data set title, location, date, acknowledgments, etc.) and a series of HTML links to associated data files and related data sets. Line 5 of each data file is a list of the column names, and line 6 and following lines contain the actual data.

9. Data Manipulations

9.1 Formulae

See Section 7.3.2.

9.1.1 Derivation Techniques and Algorithms

Not yet available.

9.2 Data Processing Sequence

9.2.1 Processing Steps

LAI-2000: In-stand files from one or two LAI-2000 units were merged with an above/outside-stand reference file from another LAI-2000 unit within the program "c2000.com" to calculate the effective LAI.

TRAC: The element (leaf for aspen and shoot for conifers) clumping index was calculated for each transect measurement. A canopy gap size distribution was first calculated from the stream of transmitted PAR data, and a gap removal approach (Chen and Cihlar, 1995a) was used to calculate the clumping index.

TRAC: Measurements from the upward- and downward-facing PAR sensors were used to calculate the mean transmitted PAR and the PAR albedo of the forest floor. The above-canopy incident PAR was taken as the PAR measurements outside the stand or in large canopy gaps. The stand PAR albedo was obtained on the top of the flux tower with the TRAC or stationary PAR sensors (Chen, 1996b).

9.2.2 Processing Changes

None.

9.3 Calculations

9.3.1 Special Corrections/Adjustments

A key correction to the final LAI results is the 15% increase in the mean value of the effective LAI from the LAI-2000, according to the finding of Chen (1996b), who found that the LAI-2000 underestimates the effective LAI by about 15% in comparison with TRAC measurements, which are free from the light-scattering effect. This correction was not made in the raw transect LAI-2000 measurements but was made in the final LAI files.

9.3.2 Calculated Variables

See Section 3.

9.4 Graphs and Plots

None.

10. Errors

10.1 Sources of Error

LAI is estimated with the LAI-2000 from all light not intercepted by objects in the sensor's FOV, so foliage area index would be a more appropriate term. Some assumptions must be met for accurate estimates of foliage amount and orientation when using the LAI-2000. The degree to which these assumptions are violated will affect the degree to which the calculations can be trusted. The major assumptions are:

- The foliage is black. It is assumed that the below-canopy readings do not include any radiation that has been reflected or transmitted by foliage. There is an optical filter in the LAI-2050 (sensor head) that rejects radiation above 490 nm. In this blue portion of the spectrum, foliage typically reflects and transmits relatively little radiation.
- The foliage is randomly distributed within certain foliage-containing envelopes. These envelopes might be parallel tubes (a row crop), a single ellipsoid (an isolated bush), an infinite box (turf grass), or an infinite box with holes (deciduous forest with gaps).
- The foliage elements are small compared to the view area of each ring. An approximate guideline is this: the distance from the sensor to the nearest leaf over it should be at least four times the leaf width.
- The foliage is azimuthally randomly oriented. That is, it does not matter how the foliage is inclined, as long as all the leaves are not facing the same compass direction.
- The sky brightness is azimuthally uniform.
- Blockage of the sensor's FOV is the same amount for both incoming and transmitted readings.

No canopy conforms exactly to the first four assumptions. Foliage is never random, but is clumped along stems and branches, and is certainly not black. Many species exhibit some degree of heliotropism, which violates the azimuthal randomness assumption. However, the practical compromises that must be made are often not serious. Many canopies can be considered to be random, and living foliage does have relatively low transmittance and reflectance below 490 nm. Offsetting errors may be common, such as when leaves are grouped along stems (increasing light transmittance), but arranged to minimize overlap (decreasing transmittance). View restrictors on the LAI-2050 (sensor head) can reduce errors associated with assumptions 5 and 6 but at the potential cost of reduction of sample size.

The sensor after recalibration is 98% accurate. The major error arose from the difficulty of maintaining the sensor at a constant horizontal position during measurements. A level is mounted on the holding arm close to the sensor. While walking, the level was watched and the holding arm was adjusted instantly to keep the sensor in a level position. However, because the whole system moves at a walking pace, a slight deviation from the horizontal position is inevitable. The deviation was generally kept within 2 degrees.

10.2 Quality Assessment

10.2.1 Data Validation by Source

LAI values were compared with values obtained from different methods and values from other investigators, and the LAI results presented here have been validated with direct LAI measurements through destructive sampling (Chen et al., 1997b).

10.2.2 Confidence Level/Accuracy Judgment

LAI-2000 measurements alone considerably underestimate LAI because of the foliage clumping; i.e., the effective LAI is usually about 50% of the true LAI for conifers and 75% of the true LAI for deciduous. Hemispherical photography can provide only the effective LAI. The clumping index obtained from the TRAC and shoot sample analysis provides a critical improvement to bring optical LAI into agreement with destructive sampling results obtained by Terrestrial Ecology (TE)-06.

10.2.3 Measurement Error for Parameters

The measurement error for the final LAI is assessed to be within 25% of the reported value and daily green FPAR within 5%.

10.2.4 Additional Quality Assessments

Not available.

10.2.5 Data Verification by Data Center

BORIS staff has viewed the data and performed some basic checks before loading.

11. Notes

11.1 Limitations of the Data

The number of sites included in this investigation is too small for accurate assessment of the mean LAI and FPAR values for boreal forest. Remote sensing methods are used to extend these sites to the BOREAS region (see the document for RSS-07 AVHRR LAI and FPAR data sets). The needle-to-shoot area ratio appears to have little variation between the stands and can be taken as the representative value for boreal forests, while the element clumping index varies greatly and is largely affected by stand density. This clumping index has to be assessed for individual sites using instruments like the TRAC.

11.2 Known Problems with the Data

See Section 10.1.

11.3 Usage Guidance

There can be considerable variability in LAI values, especially in natural ecosystems. Grazing of trees can enhance the natural variability. Extreme water stress causing leaf rolling could change the effective LAI.

11.4 Other Relevant Information

The LAI-2000 is definitely a field-proven instrument. It measures the canopy gap fraction accurately, from which the effective LAI is derived accurately. No artificial influence can be easily introduced into the measurements. It is the state of the art for measuring the canopy gap fraction.

The TRAC is a recent development for measuring the canopy gap size distribution from which the effect of nonrandom foliage spatial distribution on LAI-2000 measurements of LAI can be quantified. The error in the foliage (shoot) clumping index derived using the TRAC is within 5%.

12. Application of the Data Set

These data can be used to establish relationships between LAI, FPAR, and remotely sensed radiances and their transformations.

13. Future Modifications and Plans

None given.

14. Software

14.1 Software Description
None given.

14.2 Software Access
None given.

15. Data Access

The RSS-07 LAI, gap fraction, and FPAR data are available from the Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

15.1 Contact Information
For BOREAS data and documentation please contact:

ORNL DAAC User Services
Oak Ridge National Laboratory
P.O. Box 2008 MS-6407
Oak Ridge, TN 37831-6407
Phone: (423) 241-3952
Fax: (423) 574-4665
E-mail: ornldaac@ornl.gov or ornl@eos.nasa.gov

15.2 Data Center Identification
Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) for Biogeochemical Dynamics http://www-eosdis.ornl.gov/.

15.3 Procedures for Obtaining Data
Users may obtain data directly through the ORNL DAAC online search and order system [http://www-eosdis.ornl.gov/] and the anonymous FTP site [ftp://www-eosdis.ornl.gov/data/] or by contacting User Services by electronic mail, telephone, fax, letter, or personal visit using the contact information in Section 15.1.

15.4 Data Center Status/Plans
The ORNL DAAC is the primary source for BOREAS field measurement, image, GIS, and hardcopy data products. The BOREAS CD-ROM and data referenced or listed in inventories on the CD-ROM are available from the ORNL DAAC.

16. Output Products and Availability

16.1 Tape Products
None.

16.2 Film Products
None.

16.3 Other Products
These data are available on the BOREAS CD-ROM series.

17. References

17.1 Platform/Sensor/Instrument/Data Processing Documentation

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17.3 Archive/DBMS Usage Documentation

None.

18. Glossary of Terms

None.

19. List of Acronyms

```
APAR    - Absorbed Photosynthetically Active Radiation
ASCII   - American Standard Code for Information Interchange
AVHRR   - Advanced Very High Resolution Radiometer
BOREAS  - BOReal Ecosystem-Atmosphere Study
BORIS   - BOREAS Information System
CCRS    - Canada Centre for Remote Sensing
CD-ROM  - Compact Disk-Read-Only Memory
DAAC    - Distributed Active Archive Center
dbh     - diameter at breast height
EOS     - Earth Observing System
EOSDIS  - EOS Data and Information System
FOV     - Field of View
FPAR    - Fraction of Photosynthetically Active Radiation
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GIS     - Geographic Information System
GMT     - Greenwich Mean Time
GPS     - Global Positioning System
GSFC    - Goddard Space Flight Center
HTML    - HyperText Markup Language
IFC     - Intensive Field Campaign
IPAR    - Intercepted Photosynthetically Active Radiation
IRT     - Infrared Thermometer
LAI     - Leaf Area Index
NAD83   - North American Datum of 1983
NASA    - National Aeronautics and Space Administration
NOAA    - National Oceanic and Atmospheric Administration
NSA     - Northern Study Area
OA      - Old Aspen
OBS     - Old Black Spruce
OJP     - Old Jack Pine
ORNL    - Oak Ridge National Laboratory
PAI     - Plant Area Index
PANP    - Prince Albert National Park
PPFD    - Photosynthetic Photon Flux Density
RSS     - Remote Sensing Science
SSA     - Southern Study Area
TE      - Terrestrial Ecology
TM      - Thematic Mapper
TRAC    - Tracing Radiation and Architecture of Canopies
URL     - Uniform Resource Locator
UTM     - Universal Transverse Mercator
YJP     - Young Jack Pine
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The BOREAS RSS-7 team collected various data sets to develop and validate an algorithm to allow the retrieval of the spatial distribution of LAI from remotely sensed images. Ground measurements of LAI and FPAR absorbed by the plant canopy were made using the LAI-2000 and TRAC optical instruments during focused periods from 09-Aug-1993 to 19-Sep-1994. The measurements were intensive at the NSA and SSA tower sites, but were made just once or twice at auxiliary sites. The final processed LAI and FPAR data set is contained in tabular ASCII files.

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